MEMBERSHIP IN THE INDOOR HEALTH AND PRODUCTIVITY PROJECT: FINAL REPORT

CONSULTANT REPORT

Prepared For:

California Energy Commission
Public Interest Energy Research Program

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LAWRENCE BERKELEY NATIONAL LABORATORY

AUGUST 2003
500-03-078

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Contract No. 500-99-013
Work Authorization 27

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Acknowledgements

Complementary support for this research was provided by the U.S. Department of Energy (DOE) and the U.S. Environmental Protection Agency (EPA) through the National Institute for Science and Technology (NIST). The authors acknowledge the support of Terry Logee, David Mudarri, and James Hill who served as the program managers at DOE, EPA, and NIST, respectively, and Philip Spartz and Martha Brook as the Program managers at the California Energy Commission. The initial classroom IEQ assessments in Washington and Idaho were sponsored by annual grants from the USEPA Region X office (Contracts #X-98084701-0, X-97014901-0), and a WSU Service Center Agreement with Northwest Air Pollution Authority.

The authors thank Art Rosenfeld, David Mudarri, Terry Logee, John Talbott, James Hill, William Broadt, Michael Hodgson, Richard Little, Roger Rosa, Jack Snell, and Richard Wright for their guidance provided as members of the steering committee of the indoor Health and Productivity Project.

Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research.

What follows is the final report for the Membership in the Indoor Health and Productivity Project, Contract No. 500-98-013 Work Authorization 27, conducted by the Lawrence Berkeley National Laboratory. The report is entitled "Membership in The Indoor Health and Productivity Project: Final Report to The California Energy Commission**".** This project contributes to the Buildings End-Use Energy Efficiency program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

Table Of Contents

Executive Summary

An increasingly strong body of research indicates that the quality of indoor environments can substantially affect people's health and performance and that practical improvements in indoor environmental quality could bring about many billions of dollars of annual productivity increases in the U.S. The associated broad goals of the Indoor Health and Productivity (IHP) Project are 1) to improve the communication of research findings in the IHP area to scientists and building professionals, helping to stimulate implementation of existing beneficial technologies and practices; and 2) to take advantage of highly cost effective opportunities to advance knowledge about technologies or practices for improving IHP. Many of the IHP activities, including those described in this report, have complementary funding from multiple organizations.

This final report for the Energy Commission describes two IHP activities. One major objective was to upgrade and update the IHP web site (www.ihpcentral.org), which included the expansion of the on-line IHP bibliography of technical papers. The IHP web site content was updated so that all reports from project's research are now available online. The web server and bibliographic data base were upgraded. The online bibliography is now available 24 hours per day. The maintenance of the database (browsing, searching, adding, editing, deleting) was changed so that it is now completely web-enabled. The site has a re-designed "Search Page" which is more user-friendly. It allows users to identify relevant papers quickly and efficiently. One hundred fifty seven new papers with abstracts were added to the on-line IHP bibliography, bringing the total number of papers in the bibliography to 1061. The upgraded web site and bibliography constitutes a valuable resource for researchers, architects, engineers, and facility managers.

The second key objective was to assess the relationship of classroom carbon-dioxide (CO_2) concentrations with student absence by expanding and analyzing an existing data set obtained during prior surveys in Washington State and Idaho. This work was motivated by the findings from prior research in offices, barracks, nursing homes, and jails, which suggested that higher CO_2 concentrations in classrooms, which indicate lower rates of outside air supply per occupant, would be associated with increased rates of student respiratory illness and absence. By adding data on student absence, socio-economic status, and other classroom characteristics to the existing data set, and employing multivariate statistical modeling to analyze the data, we assessed the relationship between CO_2 concentrations and absence rates, controlled for other factors that might confound the relationship, such as socio-economic status. We obtained absence data from 409 elementary-grade classrooms with independent ventilation systems. In 45% of the classrooms, the CO_2 concentration exceeded 1000 ppm, indicating that the classroom ventilation rate was clearly below the minimum rates in the ASHRAE and California Title 24 ventilation standards. A 1000 ppm increase in the difference between indoor and outdoor CO_2 concentration was associated with a 10% to 20% increase in student absence. Outside air (ventilation) rates estimated from CO_2 and other collected data were not associated with absence; however, several critical assumptions were required to estimate the ventilation rates. If the relationship between CO_2 and absence is confirmed in future studies, improving classroom ventilation should be considered a practical means of reducing student absence.

The updated IHP web site and bibliography will help researchers, architects, engineers, and facility managers in California, and elsewhere, identify effective and energy-efficient technologies and practices for improving health and productivity. The results of the classroom study, even though they are preliminary, may motivate school districts to improve classroom ventilation where it is deficient. If subsequent studies confirm that improved ventilation decreases student absence and school districts take corrective actions, the expected benefits would include: a) improved student health; b) improved student learning with associated long-term economic benefits to society; and c) increased funding to school districts because funding is linked to student attendance.

Our recommendations include additional future tasks to communicate research findings in the IHP area to scientists and building professionals, helping to stimulate implementation of energy efficient technologies or practices for improving health and productivity. Based on the analyses of the classroom data, we recommend larger studies designed specifically to investigate the linkage of longer term CO_2 concentration data and more accurately measured ventilation rates with student absence. We also recommend that highly energy efficient technologies and practices for improving classroom ventilation be developed and demonstrated, so that energy savings and absence reductions can be obtained simultaneously. Documented reductions in absence from energy efficient classroom ventilation technologies would provide a strong incentive for energy efficiency in schools.

Abstract

An increasingly strong body of research indicates that the quality of indoor environments substantially affects people's health and performance and that practical improvements in indoor environmental quality could bring about billions of dollars of annual productivity increases in the U.S. This final report describes two completed indoor health and productivity (IHP) activities. The first activity was to upgrade the IHP web site (www.ihpcentral.org), which included the addition of 157 new papers with abstracts to the on-line IHP bibliography, bringing the total number of papers in the bibliography to 1061. The upgraded web site and bibliography constitute a unique and valuable resource for researchers and building professionals. For the second activity, we supplemented an existing data set of elementary-grade classroom dioxide (CO_2) concentrations with student absence data and employed multivariate regression modeling to evaluate the relationship between CO_2 concentrations and absence rates, controlled for other factors such as socio-economic status. In 45% of the classrooms, the CO_2 concentration exceeded 1000 ppm, indicating that the ventilation rate was clearly below the minimum rate in the ASHRAE and California Title 24 ventilation standards. A 1000 ppm increase in the difference between indoor and outdoor CO_2 concentration was associated with a 10% to 20% increase in student absence and the association was statistically significant. Ventilation rates estimated from CO_2 and other data were not associated with absence. If the relationship between CO_2 and absence is confirmed in future studies, improving classroom ventilation should be considered a practical means of reducing student absence.

1.0 INTRODUCTION

An increasingly strong body of research indicates that the quality of indoor environments can substantially affect people's health and performance and that practical improvements in indoor environmental quality could bring about many billions of dollars of annual productivity increases in the U.S. It is important to use energy-efficient technologies and practices to attain these health and productivity improvements. The associated broad goals of the Indoor Health and Productivity (IHP) Project are 1) to improve the communication of research findings in the IHP area to scientists and building professionals, helping to stimulate implementation of existing beneficial technologies and practices; and 2) to take advantage of highly cost effective opportunities to advance knowledge about technologies or practices for improving IHP. Many of the IHP activities have been co-funded by multiple organizations.

The specific objectives of the IHP research described in this report were to:

- Upgrade the IHP web site;
- Update the on-line bibliography of IHP-related papers ;
- Expand and analyze a database of classroom CO_2 concentrations and IEQ characteristics to determine if higher CO_2 concentrations are associated with a lower rate of student absence; and
- Document the methods and finding of the classroom study in a technical paper.

The remainder of this report discusses the project approach, project outcomes, and conclusions and recommendations. The technical paper based on the classroom study is included as attachment 1.

2.0 PROJECT APPROACH

2.1. Upgraded IHP Web site

The IHP web site content was updated so that all reports from project's research are now available online. The web server was changed to one available 24 hours per day every day. The web server - database - programming language was changed from Internet Information Server (IIS) - Microsoft Access - Activer Server Pages to Apache - mySQL - PHP. The maintenance of the database (browsing, searching, adding, editing, deleting) was changed so that it is now completely web-enabled. The site's "Search Page" was redesigned to make it more user-friendly.

2.2. Updated IHP Bibliography

Using the criteria established for paper selection, the following papers and abstracts were added to the IHP online bibliography available at www.ihpcentral.org.

- 100 papers from the Indoor Air 2002 conference proceedings
- 12 papers from the ASHRAE IAQ 2001 conference proceedings
- 20 papers from the Healthy Building 2000 Conference proceedings
- 25 papers identified from searches using the PubMed database

Although not promised in the scope of work, with the assistance of a no-cost student, the following improvements to the online bibliography were also implemented.

- All the papers in the IHP bibliography were tagged so that they belong to one of the seven "Reference Types", e.g., journal article, conference article, etc.
- 812 out of 1061 total papers were assigned to one of seventeen primary subject "Categories", e.g., lighting, moisture, office design, productivity, SBS, etc.
- 702 of 1061 total papers were assigned to a "Study Types", e.g., experimental research, literature review, etc.
- 191 out of 296 papers within the "Experimental research" category were classified into "Subject Size" categories.
- Pie charts were added to the IHP bibliography to show the distribution of papers either by "Reference Type" or by "Primary Category" or by "Study Type" or by "Subject Size".

2.3. Relationship Of Classroom CO_2 Concentrations With Absence Rates

From an existing database of classroom characteristics and CO_2 concentrations, we selected a set of 409 classrooms (kindergarten through grade six) with ventilation systems that served no other classroom. Attendance data were collected from the school administration offices. School administrators allowed field technicians access to school attendance sheets for entering data into a pre-formatted spreadsheet program. In one SD with seven schools, the enrollment and attendance of each individual student on each school day was recorded. For schools in all the other SDs surveyed, we recorded the number of students enrolled, the number absent, and the number in attendance for each classroom and school day.

Aggregate data were collected on demographic and socio-economic variables that could influence student absence and, thus, confound the study findings. These data were obtained for the 2001-02 school year or based on the 2000 national census from several publicly-available electronic resources. We collected data, at the school level, on gender and ethnicity (five categories). We also collected school-level data, on percent participation in subsidized free lunch programs, reduced-cost lunch programs, and the composite of the free and reduced-cost lunch programs, the latter which was used as an indicator of student socio-economic status (SES).

Based on the measured CO_2 data, we computed the difference between the measured indoor and outdoor CO_2 concentrations (dCO_2). We also used the measured CO_2 data and the measurement time to estimate the total ventilation rate, i.e., the flow rate of outside air into the classroom on the day of the CO_2 measurement prior to the measurement. This approach, however, required several assumptions to be made. The basic approach (see Attachment 1F) was to apply a transient mass balance equation for the indoor CO_2 concentration.

The data were analyzed with SAS software (Enterprise Guide version 1.3 and SAS system release 8.2, SAS Institute, Cary, NC). Descriptive statistics were calculated and the associations of independent variables with student attendance or absence were determined using multivariate linear regression models. Models were developed for annual average daily attendance (ADA), for ADA prior to the classroom surveys and CO2 measurements, and for annual average absence as dependent variables. Independent variables in the final models were: 1) dCO_2, ventilation rate, or ventilation rate per person, as continuous variables; 2) the composite percentage of students at a school participating in subsidized free and reduced-cost lunch programs as an indicator of student and family SES; 3) grade level; 4) type of classroom – traditional or portable; 5) the state in which the classroom was located; and 6) the percentages of Hispanic and/or White/Caucasian students in the school as an indicator of ethnic composition.

3.0 PROJECT OUTCOMES

The outcomes of this project were as follows:

- **The IHP web site was upgraded** - The upgraded IHP web site now contains the results of all prior IHP projects. The site was made accessible continuously, rather than the former case with access during working hours. The maintenance of the database (browsing, searching, adding, editing, deleting) was changed so that it is now completely web-enabled. The site's "Search Page" was redesigned to make it more user-friendly.
- **The IHP on-line bibliography was updated** - The IHP online bibliography now contains 157 new IHP papers with abstracts. The bibliography was made more user friendly by adding the following searchable fields that help users quickly identify papers of interest: reference type; subject category, study type, and subject size. Pie charts were added to the IHP bibliography to show the distribution of papers either by "Reference Type" or by "Primary Category" or by "Study Type" or by "Subject Size.
- **Higher CO_2 concentrations were determined to be associated with increased student absence rates** - We obtained absence data from 409 elementary-grade classrooms with independent ventilation systems. In 45% of the classrooms, the CO_2 concentration exceeded 1000 ppm, indicating that the classroom ventilation rate was clearly below the minimum rates in the ASHRAE and California Title 24 ventilation standards. A 1000 ppm increase in the difference between indoor and outdoor CO_2 concentration was associated with 10% to 20% increase in student absence, and the associations were statistically significant. Outside air (ventilation) rates estimated from CO_2 and other collected data were not associated with absence. Another finding of interest was that absence rates were significantly higher in portable classrooms than in traditional classrooms.
- **A technical paper suitable for submission to a journal was written based on the classroom study** - This technical paper (Shendell et al, 2003) documents the study objectives, methods, and findings and will be submitted to Indoor Air Journal. A copy is provided in Attachment 1.

4.0 CONCLUSIONS AND RECOMMENDATIONS

4.1. Conclusions

- An upgraded IHP web site and on-line bibliography have been produced and constitute a unique and valuable resource for researchers, architects, engineers, and facility managers
- The data from classroom study corroborates prior information indicating that ventilation rates in many classrooms do not meet current minimum ventilation standards.
- The analyses of the classroom data provide preliminary evidence that improvements in classroom ventilation would substantially decrease rates of student absence. If the findings are confirmed in future studies, improving classroom ventilation should be considered a practical means of reducing student absence, which would be expected to improve student learning.

4.2. Commercialization Potential

- The IHP web site and bibliography are unique resources. The site is identified as a link in other related web sites, such as that of the US EPA and the Lawrence Berkeley National Laboratory. Actions should be taken (see recommendations) to increase the number of researchers and stakeholders who are aware of, and thus use, the online web site and the associated bibliography.
- The results of the classroom study will be submitted for publication. Before efforts are taken to encourage a widespread response to the findings by those who produce and operate classrooms, we believe the findings should be confirmed in future studies.

4.3. Recommendations

- We recommend continued support of IHP activities designed: a) to improve the communication of research findings in the IHP area to scientists and building professionals, helping to stimulate implementation of energy efficient technologies or practices for improving health and productivity; and b) to take advantage of highly cost effective opportunities to advance knowledge about technologies or practices for improving IHP. In support of the first of these two goals, the IHP web site and bibliography should undergo a major update every two to three years. Summaries of key IHP papers that have practical implications should be published every two to three years in a journal widely read by building professionals. We also recommend increasing the number of links on the IHP web site to related sites beyond the 19 existing links. In particular, additional links to IHP-related organizations and research centers should be added.
- No explicit effort has been taken to encourage the managers of other web sites to include a link to the IHP web site and bibliography, although several such links have been established. To increase awareness and utilization of the IHP web site and bibliography, we recommend that the owners of other related web sites be asked to add a link to the IHP web site. In addition, the IHP project and web site should continue to be communicated to stakeholders in presentations, articles, and newsletters.

- Because the classroom study was based on analyses of existing data with some scientific limitations, general conclusions should not be drawn from the observed linkage of higher CO_2 levels with increased absence. However, based on the study findings, we recommend larger studies designed specifically to investigate the linkage of longer term CO_2 concentration data and more accurately measured ventilation rates with student absence. We also recommend that highly energy efficient technologies and practices for improving classroom ventilation be developed and demonstrated, so that energy savings and absence reductions can be obtained simultaneously. Documented reductions in absence from energy efficient classroom ventilation technologies would provide a strong incentive for energy efficiency in schools. After the results of this research are available, recommendations should be developed for improvements in minimum ventilation standards for classrooms.
- The steering committee of the IHP project has recommended that the knowledge of leading IAQ investigators about how to prevent IHP-related problems be compiled and broadly communicated. The authors agree with this recommendation.
- To date, there have been five sponsors for IHP activities. We recommend that efforts be taken to broaden the base of sponsors.

4.4. Benefits to California

- The updated IHP web site and bibliography will help building professionals in California identify energy-efficient technologies and practices for improving health and productivity.
- The results of the classroom study, even though they are preliminary, are quite provocative and may motivate school districts to improve classroom ventilation where it is deficient. If subsequent studies confirm that improved ventilation decreases student absence and school districts take corrective actions, the expected benefits would include: a) improved student health; b) improved student learning with associated long-term economic benefits to society; and c) increased funding to school districts because funding is linked to student attendance.

5.0 REFERENCES

Derek G. Shendell, Richard Prill, William J. Fisk, Michael G. Apte, David Blake, David Faulkner (2003). Associations between classroom CO_2 concentrations and student attendance. Lawrence Berkeley National Laboratory Report. To be submitted to Indoor Air.

ATTACHMENT 1

LBNL-53586

To be submitted to INDOOR AIR

ASSOCIATIONS BETWEEN CLASSROOM CO_2 CONCENTRATIONS AND STUDENT ATTENDANCE

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July 25, 2003

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ABSTRACT

Student attendance in American public schools is a critical factor in securing limited operational funding. Student and teacher attendance influence academic performance. Limited data exist on indoor air and environmental quality (IEQ) in schools, and how IEQ affects attendance, health, or performance. This study explored the association of student absence with measures of indoor minus outdoor carbon dioxide concentration (dCO_2). Absence and dCO_2 data were collected from 409 traditional and 25 portable classrooms from 14 schools located in six school districts in the states of Washington and Idaho. Study classrooms had individual heating, ventilation, and air conditioning (HVAC) systems, except two classrooms without mechanical ventilation. Classroom attributes, student attendance and school-level ethnicity, gender, and socioeconomic status (SES) were included in multivariate modeling. Forty-five percent of classrooms studied had short-term indoor CO_2 concentrations above 1000 parts-per-million (ppm). A 1000 ppm increase in dCO_2 was associated ($p < 0.05$) with a 0.5% to 0.9% decrease in annual average daily attendance (ADA), corresponding to a relative 10% to 20% increase in student absence. Outside air (ventilation) rates estimated from dCO_2 and other collected data were not associated with absence. Annual ADA was 2% higher ($p < 0.0001$) in traditional than in portable classrooms.

PRACTICAL IMPLICATIONS

This study provides motivation for larger school studies to investigate associations of student attendance, and occupant health and student performance, with longer term indoor minus outdoor carbon dioxide concentrations and more accurately measured ventilation rates. If our findings are confirmed, improving classroom ventilation should be considered a practical means of reducing student absence. Adequate or enhanced ventilation may be achieved, for example, with educational training programs for teachers and facilities staff on ventilation system operation and maintenance. Also, technological interventions such as improved automated control systems could provide continuous ventilation during occupied times, regardless of occupant thermal comfort demands.

KEYWORDS

carbon dioxide, schools, children, ventilation, attendance

INTRODUCTION

Existing information on the relationships between indoor air and environmental quality (IEQ) in classrooms and student absence, health, or academic performance is limited and has been reviewed by Heath and Mendell (2002) and Daisey et al. (2003). There have been a few studies of the associations of student health, and to a lesser extent student absence or learning, with types of ventilation system, ventilation rates, indoor temperature and humidity, concentrations of chemical and microbiological pollutants, and amount of daylight (Pepler, 1968; Green, 1974, 1985; Norback et al., 1990; Ruotsalainen et al., 1995; Myhrvold et al., 1996; Myhrvold and Olsen, 1997; Smedje et al., 1997; Walinder et al., 1997a, 1997b, 1998; Meyer et al., 1999; Ahman et al., 2000; Smedje and Norback, 2000, Kim et al., 2002; Sahlberg et al., 2002; Heschong 2002). Some, but certainly not all, studies have found measured IEQ parameters were associated with health, performance, or absence.

Total ventilation, a combination of unintentional air infiltration through the building envelope, natural ventilation through open doors and windows, and mechanical ventilation, provides a means for reducing indoor concentrations of indoor-generated air pollutants. Ventilation standard 62 developed by ASHRAE (2001) specifies a minimum ventilation rate of 7.5 L s^{-1} (15 ft^3 min^{-1}) per occupant for classrooms. Ceiling- or wall-mounted heating, ventilation and air conditioning (HVAC) systems are often used to mechanically ventilate classrooms, although these HVAC systems may provide less ventilation than intended due to design and installation problems, poor maintenance, and because HVAC systems are often not operated continuously during occupancy.

Since measuring the actual ventilation rate is expensive and potentially problematic, the indoor concentration of carbon dioxide (CO_2) has often been used as a surrogate for the ventilation rate per occupant, including in schools (e.g., Lee and Chang, 1999). Indoor CO_2 concentrations exceed outdoor concentrations due to the metabolic production of CO_2 by building occupants. For example, for adult office workers, assuming a ventilation rate of 7.5 L s^{-1} per person and a typical outdoor CO_2 concentration of 350-400 parts-per-million (ppm), a steady state indoor CO_2 concentration of 1000 ppm has been used as an informal dividing line between "adequate" and "inadequate" ventilation (ASHRAE, 2001). However, a CO_2 concentration is only a rough surrogate for ventilation rate, primarily because the measured concentration is often considerably less than the steady state concentration. Despite the limitations of CO_2 concentrations as a measure of ventilation rate, higher concentrations have been associated with increased frequency of health symptoms and increased absence in studies of office workers (Erdmann et al.. 2002; Milton et. al 2000). Available data have indicated many classrooms with ventilation rates below the code minimum or with CO_2 concentrations above 1000 ppm (e.g., Carrer et. al, 2002; Daisey et al., 2003; Shendell et al., 2003a; Lagus Applied Technologies, 1995; RTI, 2003). Therefore, the extent to which lower ventilation rates affect student health, absence, and performance is of particular interest. In general, school absenteeism can serve as an indicator of the student or teacher's overall health condition, although attendance patterns result from a complex interaction of many factors (Weitzman, 1986; Alberg et al., 2003).

This paper presents the results of a study which expanded the work of Prill et al. (2002), who reported findings from rapid IEQ assessment surveys in public schools, including short-term CO_2 measurements in the indoor air, outdoor air, and HVAC supply air diffuser. The present study's hypothesis explored if higher indoor minus outdoor CO_2 concentrations (dCO_2) are associated with increased student absence.

METHODOLOGY

Recruitment of classrooms

Primary and secondary schools in the states of Washington (WA) and Idaho (ID) were approached in the 2000-01 and 2001-02 school years to participate in the Washington State University (WSU) and the Northwest Air Pollution Authority (NWAPA) "3 Step IEQ Program," a streamlined approach for implementing the U.S. EPA's "Tools for Schools" program (Prill et al., 2002). These schools had attended IEQ workshops conducted by WSU or NWAPA, had contacted WSU or NWAPA for IEQ assistance, or were recommended to WSU and NWAPA by other participant school districts (SDs). To select our sample of schools from this group of K-12 schools (n=224), we used a two-step process. First, we only considered primary schools serving K-5 or K-6 (n=134), excluding special education and day care buildings. Second, due to limited resources and travel logistics, we focused on: 1) schools in cities or SDs with the most primary schools; 2) schools where the majority of classrooms were served by individual HVAC systems (or none if just wall heaters were used); and, 3) schools from which daily attendance data, at the student or classroom level, were available. Individual HVAC systems included wall- and ceiling-mounted unit ventilators or heat pumps for heating and/or air conditioning. We excluded classrooms in buildings where one HVAC system served multiple classrooms and classrooms with unvented space heaters for permanent heating systems. The final study sample, after some schools could not participate because they lacked appropriate attendance data records, and given available resources, consisted of 436 classrooms from 22 schools (14 in WA, 8 in ID) in 6 SD (4 in WA, 2 in ID).

IEQ Assessments and CO_2 measurements

The IEQ assessments performed in every classroom consisted of walk-through surveys conducted by a technician together with relevant facilities and administrative staff, and short-term measurements of CO_2 during school hours (Prill et al. 2002). CO_2 measurements were conducted by WSU field technicians using the Q-TRAK Model 8551 instrument (TSI, Inc., Shoreview, MN, USA). Inside each classroom, two short-term (< five-minute average) measurements were conducted sequentially and the measurement times were recorded. First, indoor air CO_2 was assessed near the center of the classroom at the breathing zone height of seated students, but at least one meter from students and not directly underneath the supply air diffusers. Second, the CO_2 concentration in the HVAC supply air was measured using a capture hood to direct undiluted supply air into the instrument sensor. CO_2 instruments were calibrated weekly according to manufacturer specifications using "zero" (N_2, 99.99% pure) and "span" (2010 ppm CO_2, +/- 2%) gases. Instruments were also cross-compared during short-term (< five-minute average) outdoor air CO_2 measurements at each school at locations distant from potential CO_2 sources.

Attendance data

Attendance data were collected from school administrative staff who allowed field technicians access to school attendance records to enter data into a pre-formatted spreadsheet program. For seven schools of one SD, the enrollment and attendance of each individual student on each school day was recorded. For schools in every other SD, we recorded the number of students enrolled, the number absent, and the number in attendance for each classroom and school day. The daily percentages of students in attendance were calculated by pre-coded formulae. Attendance data received a quality control review by LBNL after WSU field technicians sent computer files. This process verified "0" or "blank" (student present) or "1" (student absent) was entered into every cell, vacation periods were left blank, file name room number and grade level designations matched those on the worksheet, and changes in enrollment during the school year were noted with gray-shaded cells. The average daily attendance (number of students attending class divided by number of students enrolled, then converted to a percentage) was calculated for the entire school year and is denoted by "annual ADA" or "yearly attendance." In addition, the same parameter was calculated for the portion of the school year prior to the IEQ inspection and is denoted "pre-visit ADA" or "pre-visit attendance." Although the pre-visit ADA was based on less data than the annual ADA, it was also not affected by any post-inspection ventilation rate changes motivated by recommendations of the inspectors. Annual average absence was calculated as unity minus annual ADA.

Demographic and socioeconomic variables

Aggregate data were collected on demographic and socio-economic variables that could influence student absence and, thus, confound the study findings. These data were obtained for the 2001-02 school year or based on the 2000 national census data available from several public electronic resources[1]. Ferris et al. (1988) reported data on gender and age (grades) helped explain observed variance in absenteeism. Haines et al. (2002) found the percentage of students in a grade level eligible for subsidized (free) meals at school was related to the average socio-economic status (SES) of the school enrollment in that grade. We collected data, at the school level, on gender and ethnicity (five categories). We also collected school-level data on percent participation in subsidized free lunch programs, reduced-cost lunch programs, and the composite of the free and reduced-cost lunch programs; the composite was used as an indicator of student SES.

CO_2 metric

Based on the measured CO_2 data, we computed the difference between the measured indoor and outdoor CO_2 concentrations (dCO_2). Previous research on CO_2 in school classrooms (Fox et al., 2003) demonstrated a single monitoring location was appropriate for characterizing such indoor contaminant levels when HVAC systems were on, i.e., air was well-mixed. The dCO_2 is only a rough surrogate for ventilation rate because it is based on one-time short-term measurements made at a wide range of times

[1] ID Department of Education (http://www.sde.state.id.us); WA Office of the Superintendent for Public Instruction (http://www.k12.wa.us/edprofile, http://www.k12.wa.us/ → OSPI Programs → child nutrition, data administration, demographics, statistics); National Center for Educational Statistics (http://nces.ed.gov/ccd/schoolsearch).

throughout the school day. The major advantage of dCO_2, relative to the ventilation rate estimate described below, is dCO_2 does not rely on any other assumptions.

Estimated ventilation rate

We also used the measured CO_2 data and the measurement time to estimate the total ventilation rate (Q), i.e, the flow rate of outside air into the classroom on the day of the CO_2 measurement prior to the measurement. This approach, however, required several assumptions to be made. The basic approach was to apply the transient mass balance equation for the indoor CO_2 concentration

$$C(t) = \Big(\big(C(\tau) - ((G / Q) + C_o)\big)*EXP\big((-Q / V)*(t-\tau)\big)\Big) + (G / Q) + C_o \qquad \textbf{(1)}$$

where: t is the time of day; τ is the time at the start of the time period for which equation 1 is applied; C is the indoor CO_2 concentration; G is the classroom indoor CO_2 generation rate; Q is the ventilation rate (i.e., flow rate of outside air into the classroom, assumed steady); C_o is the outdoor CO_2 concentration; and V is the estimated classroom volume. We used equation 1 iteratively to determine which value of Q best predicted the measured indoor CO_2 concentration at the recorded measurement time. For these calculations, equation 1 was used for up to eight of the following sequential time periods, P1- P8: P1 = the 30 minutes before arrival of students; P2 = start of school to start of morning recess; P3 = morning recess; P4 = end of morning recess to start of lunch; P5 = lunch; P6 = end of lunch to start of afternoon recess; P7 = afternoon recess; P8 =end of afternoon recess to end of school. During P1, we assumed the teacher was present alone and, therefore, G equaled the CO_2 generation rate of an average adult office worker, which is 0.31 L min^{-1} (ASHRAE, 2001). During P3, P5, and P7, we assumed no one was in the classroom, thus, G equaled zero. When a school did not schedule morning and/or afternoon recess for certain grades, the calculations for those classrooms were adjusted accordingly. During other periods we assumed one teacher and N students were present in the classroom. The estimated generation rate of CO_2 from each student varied with grade level as discussed below. The number of students, N, was based on the number attending class on the school day, obtained from the attendance records. The calculation for period P1 assumed indoor CO_2 concentrations at the start of P1, following the overnight period without occupancy, equaled the outdoor CO_2 concentration.

Substantial effort was required to estimate the rate of CO_2 generation by the students and the resulting estimate has uncertainty, mainly because primary school children's activity levels vary during school. Based on data from Treuth et al. (1998), the 24-hour average CO_2 generation rate of age 10 children (equal numbers of boys and girls) with normal activities is 0.216 L min^{-1}. The basal CO_2 generation rate of the same children was 0.147 L min^{-1}, where basal refers to awake and inactive after a period of rest and no food intake. During sleep, the age 10 children generated 0.132 L min^{-1} of CO_2. With these data, assuming 10 hours of sleep, we calculated the ratio of CO_2 generation when active to the basal CO_2 generation rate to be 1.88, and 10 year old children generate 0.276 L min^{-1} of CO_2 when they are active (not sleeping, with normal activities). We used this rate of CO_2 generation to estimate a student's rate of CO_2 generation at school. To account for the different ages of students at different grade levels, the CO_2 generation of age 10 children was scaled linearly with basal metabolic rate, which is provided as a function of age by ICRP (1993). The resulting equation for CO_2 generation of school children by student age (grade) was:

$$G_{student} = \left((0.0257)*(\text{grade level} + 6) + 0.743\right)*(0.276), \text{ in L min}^{-1} \qquad \textbf{(2)}$$

We must emphasize, however, this equation has not been verified.

There are several sources of error in the estimated ventilation rates. Perhaps most important is the application of the standard classroom schedule for the day of CO_2 measurements. If, for example, the actual schedule deviated from the assumed standard schedule because students did not exit the class for recess, large errors could result. In addition, the calculated CO_2 generation rates of the students have uncertainties and inter- and intra-individual variability, and the classrooms volumes were assumed similar by classroom type at each school. Even without these errors, the yearly-average ventilation rate could differ substantially from the estimated rate on the day of CO_2 measurements. This would be true even if a tracer gas protocol was implemented during the classroom visits to more accurately measure classroom ventilation rates.

Multivariate Analyses

The data were analyzed with SAS software (Enterprise Guide version 1.3 and SAS system release 8.2, SAS Institute, Cary, NC). Descriptive statistics were calculated and the associations of independent variables with student attendance or absence were determined using multivariate linear regression models (ANOVA, PROC GLM). Models were developed for annual ADA, pre-visit ADA, and annual average absence as dependent variables. Independent variables in the final models were: 1) dCO_2, ventilation rate, or ventilation rate per person, as continuous variables; 2) the composite percentage of students at a school participating in subsidized free and reduced-cost lunch programs as an indicator of student and family SES; 3) grade level; 4) type of classroom – traditional or portable; 5) the state in which the classroom was located; and 6) the percentages of Hispanic and/or White/Caucasian students in the school as indicators of ethnic composition.

Depending on the terms in the model, certain data were excluded because the values of one or more input parameters were missing. First, the two classrooms in WA with no mechanical HVAC system and the five classrooms with students in more than one grade level were excluded. Second, calculated ventilation rates included four classrooms with negative values, and so we excluded these classrooms from analyses where ventilation rate was the primary independent variable.

RESULTS

Descriptive Statistics

The average primary school was about 45 years old and most (94%) classrooms were in the main building, i.e., traditional, not portables. There was a fairly equal distribution of classrooms visited across the seven grades except 6th grade classrooms were visited relatively less often because many primary schools in our study only included K-5th grades. Visits to study classrooms were fairly well distributed throughout the school day, although the least number of visits occurred during unoccupied periods. Overall, about 19 of every 20 classrooms in this study were found with the HVAC system on or cycling automatically between on or off. About nine of every 10 classrooms visited were found with windows to the outside closed. In this study, 45% of visited classrooms had measured short-term indoor CO_2 concentrations above 1000 ppm (59% in ID and 35% in WA). Median estimated ventilation rates expressed in air changes per hour (ACH) were highest in portables in WA (3.8 hr^{-1}) and lowest in portables in ID (0.7 hr^{-1}); however, these medians were based on a small sample of 25 total portable classrooms. In traditional classrooms, median estimated ventilation rates were similar (2.2 hr^{-1}) across states, although the mean ACH was higher in classrooms in ID (3.4 hr^{-1}) than in WA (2.6 hr^{-1}). Across states, grades, and room types, the geometric mean annual absence was 5% (median 4.9%, arithmetic mean 5.2%); the mean and median annual ADA were 95%.

Results of multivariate analyses

The primary results of the multivariate modeling are provided in Table 1. The dCO_2 variable was statistically significantly ($p < 0.05$) associated with both the annual

ADA and with the pre-visit ADA. For annual ADA, the parameter estimate indicated a 0.5% absolute decrease in attendance, corresponding to a 10% relative increase in the average 5% absence rate, per 1000 ppm increase in dCO_2. For the pre-visit ADA, the parameter estimate indicated a 0.9% absolute decrease in attendance, corresponding to a relative 20% percent increase in the average 5% absence rate, per 1000 ppm increase in dCO_2. The estimated ventilation rate, Q, was not associated with either absence variable.

The traditional classroom type, relative to a portable classroom, was associated with approximately a 2% increase in attendance, and with a 2.5% decrease in absence. In each case, the associations were statistically significant ($p < 0.01$).

A one percent increase in the SES variable, representing the percentage of students receiving free or reduced cost lunch, was associated ($p < 0.001$) with a 0.03% to 0.04% decrease in attendance, and with a 0.02% increase in absence ($p < 0.001$). A one percent increase in the percent of Hispanic students was associated ($p < 0.02$) with a 0.03% *increase* in attendance, and with 0.05% *decrease* in absence ($p < 0.001$).

In most models, the state variable was not associated with attendance and the corresponding parameter estimate was unstable (results not included in Table 1).

Table 1. Key results of multivariate regression modeling.[1]

Basic Model Characteristics				CO_2 or vent. rate variable		room type variable [2]		SES variable[3]		ethnicity variable[4]	
No. of class-rooms	attendance or absence variable	CO_2 or vent. rate variable in model	Model R^2	Parameter estimate	p-value	Parameter estimate	p-value	Parameter estimate	p-value	Parameter estimate	p-value
395	Yearly attendance %	dCO_2	0.21	-0.0005	0.02	2.29	<0.001	-0.026	0.0003	0.026	0.001
395	Pre-visit attendance %	dCO_2	0.18	-0.0009	0.001	2.33	<0.001	-0.037	<0.0001	0.029	0.02
392	Yearly absence %	Vent. Flow Rate	0.20	-0.1961	0.67	-2.53	<0.001	0.022	0.0007	-0.046	<0.001
392	Yearly absence %	Vent. Flow per person	0.20	0.0035	0.67	-2.53	<0.001	0.022	0.0009	-0.047	<0.001

[1]Parameter estimates represent percent increase in attendance or absence per ppm CO_2, 1 m^3 s^{-1} ventilation rate; or percent increase in the SES or ethnicity variable, or for a traditional classroom relative to a portable classroom. The P-values for the total model were always < 0.0001.

[2]For traditional/main building classrooms relative to portable/relocatable classrooms.

[3]The variable represented the percentage of students at the school receiving either free or reduced lunches.

[4]Percent Hispanic, in some models percent white/Caucasian was also included and significantly associated with attendance.

DISCUSSION

In this study, 1000 ppm increases in the difference between indoor and outdoor CO_2 concentrations were associated with 10% to 20% relative increases in student absence, and the associations were statistically significant. These findings of this study are generally consistent with those of Milton et al. (2000), who found a 50% reduction in ventilation rates in offices, with corresponding increases in indoor CO_2 concentrations, was associated with a 50% increase in short term absence among the office workers occupying the buildings. One potential explanation for our findings and those of Milton et al. (2000) is lower rates of ventilation, indicated by higher CO_2, caused increased communicable respiratory illnesses, probably by increasing the indoor concentration of airborne infectious particles produced during coughing or sneezing. In a review of the literature, Fisk (2000) summarized three studies reporting a reduction in ventilation rate was associated with increases in confirmed respiratory illness.

Because the CO_2 measurements in this study were short-term, five-minute, measurements made on a single school day at variable times of day, they should be considered only rough surrogates for the long-term average classroom ventilation rates that may affect long-term average absence rates. In general, random[2] errors in an independent variable, in this case the errors from using short-term CO_2 as a measure of long-term average ventilation rate, will tend to obscure and weaken associations with the dependent variable (in this case, attendance or absence). Our estimation of ventilation rates based on the measured CO_2 concentrations, the measurement times, and the standard classroom schedules by school by grade were an attempt to derive a ventilation rate estimate with less error. We expected the ventilation rate estimate to be more strongly associated with student absence; however, associations were not close to being statistically significant. There are two potential interpretations for the discrepancy between the dCO_2 and the ventilation-rate findings. The ventilation rate estimates may have large errors due to the uncertain assumptions mentioned in the methodology

[2] Errors that are not correlated with the value of the dependent variable

section of this paper. Alternatively, the ventilation rate estimates could be more reliable than the dCO_2 data for estimating long term average ventilation rates, suggesting the association of dCO_2 with absence was spurious and due to confounding or systematic bias.

We are not aware of large uncontrolled sources of bias likely to create erroneous associations of higher dCO_2 concentrations with increased absence. The models contain variables controlling for SES, classroom type, grade level, ethnic composition, and the State in which the classrooms are located. Thus, we have controlled for the most obvious sources of confounding bias. However, it is still possible some unknown classroom factor, which increases absence rates, is positively correlated with the measured classroom CO_2 concentrations.

This study confirms previous findings of high CO_2 concentrations in classrooms, which indicated classroom ventilation rates were often below the minimum rates specified in codes. In this study, almost half of the CO_2 concentrations were above 1000 ppm and 4.5% were above 2000 ppm. If the measured CO_2 concentrations had been maximum or steady state values, a substantially larger proportion would be expected to exceed 1000 ppm. Thus, it is likely more than half of the classrooms in this study had ventilation rates less than specified in current minimum ventilation standards.

The substantially higher rate of absence in portable classrooms, relative to traditional classrooms, is notable. We do not have a clear explanation for this finding. It is not known whether portable classrooms have inferior IEQ relative to traditional classrooms, though recent evidence in Los Angeles County has suggested relatively higher indoor air concentrations of toxic and odorous volatile organic compounds are possible in portable classrooms (Shendell et al., 2003b). In addition, it is not known whether inferior IEQ could cause such a large increase in absence. Although the higher absence rate in portable classrooms was statistically significant, the small sample (25 classrooms) should be considered. Before drawing conclusions, other studies should compare absence rates in portable and traditional classrooms.

Finally, we note how changes in ventilation or in any other factor affecting student attendance will influence the funding provided to many SDs, because funding is linked to annual ADA. For example, in California the most currently available (2001-02) funding rate is $12.08 per student-day not absent (CDE, 2003). For a classroom of 20 children with a 185-day school year (3700 student-days), a 1% decrease in annual ADA (or 20% relative increase in absence) is $450 per classroom in funding lost to the SD.

CONCLUSIONS

The major findings of this study were as follows:

- A 1000 ppm increase in the elevation of the indoor CO_2 concentration above the outdoor concentration was associated ($p < 0.05$) with a 0.5% to 0.9% decrease in yearly attendance, corresponding to a relative 10% to 20% relative increase in student absence.
- An estimated outside air supply (ventilation) rate, based on CO_2 measurements and classroom schedules, was not associated with absence.
- Yearly attendance was 2% higher ($p < 0.0001$) in traditional than in portable classrooms.

- Based on the measured CO_2 concentrations, we estimated ventilation rates in at least 50% of the classrooms were less than 7.5 L s^{-1} per person, which is the minimum rate specified in most codes and standards.
- Since this study was based on analyses of previously collected CO_2 data, general conclusions should not be drawn from the observed linkage of higher CO_2 levels with increased absence. This study, however, does provide motivation for larger studies designed specifically to investigate the linkage of longer term CO_2 concentration data and more accurately measured ventilation rates with student absence.

ACKNOWLEDGEMENTS

We thank Mark Mendell and Christine Erdmann for reviewing a draft of this document, Elisabeth Overholt and Frankie Robison, and participant school districts, school principals, and office administrative staff for their help during retrospective collection of attendance and daily schedule data. We thank the custodians and teachers visited by field technicians during school hours for their cooperation.

This report was prepared as a result of work sponsored by the California Energy Commission (Commission) and the University of California (UC). It does not necessarily represent the views of the Commission, its employees, or the State of California. The Commission, the State of California, its employees, and UC make no warranty, express or implied, and assume no legal liability for the information in this report; nor does any party represent that the use of this information will not infringe upon privately owned rights. This report has not been approved by the Commission nor has the Commission passed upon the accuracy or adequacy of the information in this report.

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This work was also supported by the National Institute for Standards and Technology with funding from the U.S. EPA Indoor Environments Division and from the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technology Program of the U.S. Department of Energy under contract DE-AC03-76SF00098. The initial classroom IEQ assessments in Washington and Idaho were sponsored by annual grants from the USEPA Region X office (Contracts #X-98084701-0, X-97014901-0), and a WSU Service Center Agreement with NWAPA renewed annually.

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